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(NASA-CR-175245) PETROLOGIC AND GEOPHYSICAL SOURCES OF LONG-WAVELENGTH CRUSTAL MAGNETIC ANOMALIES Final Technical Report, 1 Jun. 1980 - 30 Apr. 1983 (Johns Hopkins Univ.) 12 p HC A02/MF A01 CSCL 08G G3/46
N84-28276
Unclas
13947

Final Technical Report

for the period

1 June 1980 to 30 April 1983

on agreement

NAG5-35 and Supplements #1 and #2

between

NASA

and

The Department of Earth and Planetary Sciences

The Johns Hopkins University, Baltimore, MD 21218

entitled

"Petrologic and Geophysical Sources of Long-Wavelength

Crustal Magnetic Anomalies"

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This final report is a detailed review of our research efforts from 1 June 1980 to 30 April 1983. During this interval our work was funded in its entirety through agreement NAG5-35 and Supplements #1 and #2 to this agreement. The focus of our work has been "The Petrologic and Geophysical Source of Long-Wavelength Crustal Magnetic Anomalies." The research reviewed here was the thesis subject of Charles Schlinger, a graduate student of B. D. Marsh, the principal investigator.

Our study has specifically addressed the magnetic mineralogy and magnetic properties of the deep crust as they pertain to the interpretation of long-wavelength, or regional, crustal magnetic anomalies in satellite magnetic data and near-surface magnetic data. Our conclusions have relevance to the understanding of regional magnetic anomalies in both POGO and MAGSAT (magnetic field measuring satellite missions) data. We may also bring these results to bear on problems of magnetization at depth in the earth's crust. Necessarily, this research has been multifaceted and interdisciplinary. There are three separable studies, each of which stand alone. The first and second of these are:

1) A synthesis of available information of regional magnetic anomalies and the magnetization of metamorphic and igneous rocks.

2) A detailed field, analytical, and experimental study of in-situ and laboratory specimens from Lofoten and Vesteraalen, Northern Norway, --a terrain that offers exposures of high-grade granlite facies rocks that have associated regional magnetic and gravity anomalies.

These two studies are here reviewed briefly. A complete description is given in the attached copywrited manuscript. This work is the subject of several concise papers that are now in preparation.

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August 11, 1983

TO: 100.2/Grants Management Officer

FROM: 922/Geophysics Branch

SUBJECT: Final Report for NAG5-35

It is my opinion that the final report for NAG5-35, authored by Drs. Bruce D. Marsh and Charles M. Schlinger of The Johns Hopkins University and the University of Utah, respectively along with the Ph.D. dissertation to the JHU of Dr. Schlinger provide a satisfactory completion of the grant.

The thesis will serve as an invaluable reference to the magnetic properties of the Earth's crust for NASA geophysicists and the scientific community for years to come. Data determined for the Lofoten and Vesteraalen, Norway igneous and metamorphic rocks give "hard" numbers which can be applied to models of the crust where the rocks are inaccessible.

I feel that this investment has paid off very handsomely.

Herman Thomas

Herman Thomas
Science Advisor

Concur with the comments of Dr. Thomas

Charles W. Kouns

Charles W. Kouns
Technical Officer

NASA CR- 175245

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Our study has specifically addressed the magnetic mineralogy and magnetic properties of the deep crust as they pertain to the interpretation of long-wavelength, or regional, crustal magnetic anomalies in satellite magnetic data and near-surface magnetic data. Our conclusions have relevance to the understanding of regional magnetic anomalies in both POGO and MAGSAT (magnetic field measuring satellite missions) data. We may also bring these results to bear on problems of magnetization at depth in the earth's crust. Necessarily, this research has been multifaceted and interdisciplinary. There are three separable studies, each of which stand alone. The first and second of these are:

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These two studies are here reviewed briefly. A complete description is given in the attached copywrited manuscript. This work is the subject of several concise papers that are now in preparation.

Regional, or long-wavelength, magnetic anomalies, in both satellite and near-surface magnetic data, are commonly observed over continental crust. The explanation of these anomalies has has remained enigmatic by requiring, for crustal origin, laterally extensive, thick, highly magnetic, and deep seated sources. A review of the data, mathematical modeling, physical intuition, and published literature unequivocally demonstrate the necessity of a deep crustal origin of these features. We also evaluate the suggestion that certain anomalies in satellite data result from inadequate orbit computations. The principal source of error in such calculations rests with the adopted gravity field model. Such errors may play a role only for lower amplitude anomalies in older POGO satellite data.

Our main contribution, however, is a detailed field, analytical, and experimental study of rocks from Lofoten and Vesteraalen, Northern Norway, a high-grade province of deep seated origin with associated regional magnetic and gravity anomalies. We can clearly see that these rocks have a bulk magnetic character of surprising uniformity, with susceptibilities, hysteresis, and Curie temperatures, defined solely by nearly pure magnetite. Stable remanence is observed only in samples from SW Lofoten and is never of significant magnitude. The carrier of this remanence invariably appears to be hematite with 5 to 10 mole percent ilmentite in solution. Contrary to speculation the thermal enhancement of magnetic susceptibility, the Hopkinson effect, is not important in type lithologies. Rocks from the deepest part of the section have the largest average susceptibilities, $5X10^{-3}$ (c.g.s. Gaussian units), and magnitudes of nrm (natural remanent magnetization), $5X10^{-4}$emu/g. These values of susceptibility, together with the observed viscous character of the nrm, suggest that these granulite facies lithologies (particularily those of SW Lofoten) are perfect examples of deep crustal sources of typical regional magnetic anomalies.

Furthermore, these low and intermediate pressure granulites define a unique magnetic petrology, especially for mafic compositions. At higher grades of metamorphism (high-pressure granulites and eclogites) or lower grades (greenschist and amphibolite facies) such magnetite bearing assemblages will be unstable and only weakly magnetic.

Uniform remanence of thick and laterally extensive sources of regional magnetic anomalies is unlikely. In provinces analogous to Lofoten and Vesteraalen, 'Q', the ratio of nrm to induced magnetization, will typically be 1/3 to 1/2 with much of the nrm composed of a viscous remanent magnetization, or vrm. The characteristic time of regional metamorphism, cratonic cooling, and uplift, however, which is some hundreds of millions of years, is two to three orders of magnitude greater than that of uniform geomagnetic polarity. In addition, the crust of stable cratons is commonly polymetamorphic. Finally, only a size-limited class of magnetic phases can hold stable remanence under the time-temperature conditions of the deep crust; this is evident from Neel's theory of magnetic viscosity and extensions by various workers.

This evidence and these conclusions may be used to constrain models of deep crustal sources of regional magnetic anomalies over stable cratons. It portrays the deep crust as a highly magnetic unit, defined by metamorphic grade, with a Curie isotherm of 575°C (magnetite) and magnetization parallel to the ambient geomagnetic field (induced and viscous components). Collectively these results lend both credence and constraint to geophysical speculations of highly magnetic deep crustal sources of regional magnetic anomalies.

Published abstracts of talks on this material presented at national (Am. Geophys. U. and Geol. Soc. Am.) meetings are attached in Appendix I.

The third of our studies, complementing the other two, is an experimental study on magnetism of Fe_3O_4 (magnetite) at high-pressure, taking advantage of a diamond anvil type pressure cell. During the calendar years '81 and '82 Schlinger held a predoctoral fellowship at the Geophysical Laboratory of the Carnegie Institution in Washington, D.C., working with the guidance of Dr. D. Mao and Dr. P. Bell. Dr. P. Wasilewski of NASA's Goddard Space Flight Center also served as an advisor on this effort, as did Prof. B. D. Marsh. During this time interval Schlinger has devoted his time to building a non-magnetic diamond anvil type pressure cell for use in a sensitive cryogenic squid magnetometer. Magnetometers of this type are able to monitor minute changes in magnetic moment of $5 \cdot 10^{-8}$emu ($5 \cdot 10^{-11}$ A-m^2). He also spent time learning how to use these types of devices and exploring potential problems with making the actual measurements.

Not unlike most experimental programs this work has met with a number of delays, sometimes as long as 4 to 6 months. As of this writing, however, a non-magnetic, Be-Cu alloy, diamond-anvil type pressure cell with sapphire anvils and a sample capacity of 0.5 mm^3 is operational and available for experimentation. This in itself is a major hurdle overcome. A brief history of this pressure cell's development is given here.

In early 1981 Schlinger began working with a diamond anvil cell, which Dr. Peter Wasilewski at Goddard Space Flight Center had in his possession. In time it became clear that the sample volume available with diamond anvils was inadequate. Even with a cryogenic magnetometer one could not resolve the signal of the sample from that of the pressure cell. At that time synthetic sapphire anvils were ordered. These have a yield stress of $15 \cdot 10^8$ Pa or so, equivalent to 15 kb, and they allow a much larger sample, something approaching 0.5 mm^3. At this same time it also became apparent that an entirely new pressure cell was

required. The existing cell had a large remanent magnetization of $4 \cdot 10^{-7}$ emu/g, equivalent to $4 \cdot 10^{-3}$ A/m, and furthermore, it had poor mechanical characteristics.

Schlinger then contacted Dr. A. Guha of Brush-Wellman, Inc., of Cleveland, Ohio. Dr. Guha kindly agreed to a special one-time casting of a Be-Cu alloy that incorporated high purity materials. This stock was produced during the summer and fall of 1982. The material has a composition of 2% Be and 98% Cu. The hardness is reported as Rockwell C39 (A. Guha, personal communication, 1983) and the alloy has a remanent magnetization of 10^{-8} emu/g (10^{-4} A/m) or less. The components of the pressure cell were machined at the Geophysical Laboratory and sent to Brush-Wellman for heat treatment in high-purity argon gas to avoid oxidation. In May of 1983 the pressure cell was finally operational and ready for testing. Pressures of 6.3 kb ($6.3 \cdot 10^{8}$ Pa) have been attained and we forsee no problems achieving higher pressures.

We had hoped to complete a series of experiments before the conclusion of this grant period, however, unforseeable delays have forced us to postpone our plans. Even so, the fact that the cell is operational and ready for use is reassuring. As an Assistant Professor in Geophysics at the University of Utah, Salt Lake City, Schlinger will set up the apparatus necessary for continuation of this work. These plans are contingent of course upon the availability of equipment and research funds.

In summary, we feel that our accomplishments during the three years of research supported by agreement NAG5-35 and the Supplements #1 and #2 are significant in a number of ways, and of substantial benefit to NASA, the scientific community, and ourselves. We have made considerable progress towards ascribing both petrologic and geophysical significance to the deep-seated sources of regional, or long-wavelength, crustal magnetic anomalies, our original goal. We have also set up a research program to examine magnetic crustal minerals at the range of pressures found in the crust, and eventually, at higher pressures.

The Magnetic State of the Deep Crust: The Example From Lofoten & Vesterålen, North Norway

C.M. SCHLINGER (Dept. of Earth & Planetary Sci., The Johns Hopkins Univ., Baltimore, Md. 21218)
P.WASILEWSKI (NASA/Goddard Space Flight Center, Astrochemistry Branch, Greenbelt, Md. 20771)

In recent years considerable attention has been devoted to understanding the petrologic and geophysical source of regional magnetic anomalies. A profound lack of rock magnetic data has fostered unconstrained speculation. Exposures of Precambrian granulite facies assemblages and retrograded equivalents in Lofoten & Vesterålen which show regional magnetic and gravity anomalies permit examination of the magnetic mineralogy and attendant properties of rocks with an undisputed deep crustal origin. From field measurement of susceptibility and lab study of NRM and its response to AF & thermal demagnetization, hysteresis phenomena, Curie temperature, and petrography several conclusions are apparent. The oxidizing retrograde amphibolite facies event has considerably diminished the actual and potential magnetization of intermediate & felsic compositions; this is well displayed by the intrusive mangerites. Relatively intense and stable NRM ($\sim .7$ A/m) is consistently carried only by a family of retrograded Archean migmatitic gneisses in SW Lofoten. For the average sample, however, $Q<1$ and NRM is reduced to nil with AF demagnetization. Coercive fields are typically 2000 A/m. In general the exposures from the deepest levels (SW Lofoten) possess the largest induced magnetizations: 2-3 A/m (for $H= 40$ A/m). This is clear evidence that the magnetization of intermediate & alkalic regions of the deep crust is dictated by the modern geomagnetic field through induced and viscous effects and of course by thermally activated enhancement processes such as rapid VRM acquisition and the Hopkinson effect. These conclusions are in general agreement with speculation from geophysical modeling.

1. Spring Meeting

2. SCHL200596

3. C.M. Schlinger
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4. GP

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8. a) as above
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MAGNETIC MINERALOGY OF THE DEEP CRUST AND REGIONAL MAGNETIC ANOMALIES: ROCKS FROM LOFOTEN & VESTERÅLEN, NORTH NORWAY

SCHLINGER, Charles M., and MARSH, Bruce D., Dept. of Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218

The proper interpretation of regional (long wavelength) magnetic anomalies depends critically on the magnetic mineralogy and its magnetic behavior in the crust in question. Precambrian lithologies of deep crustal origin, well exposed in Lofoten and Vesterålen, permit systematic evaluation of these variables. Curie temperatures of samples from all lithologies imply that nearly stoichiometric magnetite is the dominant magnetic mineral of the deep crust. The choice of Curie isotherm for regional studies is therefore constrained to lie in the interval 555-575°C. Alternating field demagnetization of NRM, hysteresis phenomena, and susceptibility indicate that the assumption of induced magnetization is also appropriate in modelling regional anomalies. The occasional incidence of intense and stable NRM in rocks of both metamorphic and igneous origin results from exsolution of ~1μm single domain opaque oxide particles in clinopyroxene which we tentatively identify also as magnetite. One may observe this phase using conventional optical methods, however, precise chemical and mineralogical identification requires electron microscopy or possibly x-ray methods. Fine grained opaque inclusions are also found in primary (?) amphiboles, but this host is uncommon relative to the inclusion bearing clinopyroxene. Retrograde metamorphism of granulite facies assemblages to amphibolite facies (and transitional) equivalents involves the iron-titanium oxides and sulfides in that garnet, sphene, or amphibole are produced at their expense. These mineralogical changes are accompanied by reductions in NRM and saturation IRM intensities and susceptibility. In summary, these rocks suggest that modelling of the deep crust may safely assume induced magnetization with a Curie isotherm corresponding to magnetite.

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The Magnetic Petrology of the Deep Crust and the Interpretation of Regional Magnetic Anomalies

C. M. SCHLINGER and B. D. MARSH (Dept. Earth & Planetary Sciences, Johns Hopkins Univ., Baltimore, MD 21218)
P. WASILEWSKI (Lab. for Astrochemistry, Goddard Space Flight Center, NASA, Greenbelt, MD 20771)

The sources or regional magnetic anomalies are usually taken to coincide with the lower or deep crust, but the petrologic and magnetic character has only recently been considered. Through detailed field work including 4,500 measurements in Lofoten and Vesteraalen, North Norway, and laboratory, analytical, experimental, and theoretical considerations, several important general conclusions emerge. 1) The thermal enhancement of magnetic susceptibility, or Hopkinson effect, is of minimal importance. 2) Induced and viscous magnetization of high-grade rocks is defined solely by multi-domain magnetite with Curie points between 555 and 575°C (44 of 45 samples) containing but 1-2% ulvospinel. 3) Uniform remanent magnetization of laterally extensive, thick, crustal sources is unlikely; the characteristic time of cooling and uplift is 2 to 3 orders of magnitude greater than that of uniform geomagnetic polarity, stable cratons are polymetamorphic, and, the time-temperature conditions in the deep crust do not favor stability of fossil remanence. 4) Low and intermediate pressure granulites define a unique, highly magnetic petrology, especially for mafic rocks, which at higher grades (high-pressure granulites and eclogites) and lower grades (amphibolite and green-schist facies) is unstable and nonmagnetic. This is especially evident from petrographic and magnetic properties of Lofoten and Vesteraalen samples and from experiments (e.g. Green & Ringwood). 5) In SW Lofoten the rocks from the deepest section have the largest average susceptibilities, 0.005 (c.g.s.), and nrm, 0.0005 emu/g. This evidence portrays the lower crust as a highly magnetized unit whose spatial position depends critically on metamorphic grade with a Curie isotherm of 575°C and magnetization parallel to the ambient field. This gives credence to geophysical speculations of highly magnetic deep crustal sources of regional magnetic anomalies.

1. Spring Meeting
2. SCHL200596
3. Dept. Earth & Planetary Sciences
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5. Special Session: Geological Interpretation of Long-Wavelength Magnetic Anomalies
6. 0
7. 25% at Spring AGU '82 and Fall GSA '82
8. as above, attn: Mrs. Jean Suter
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